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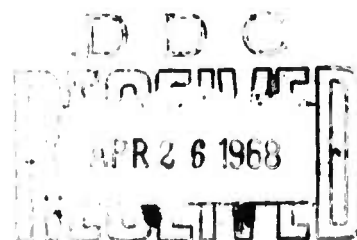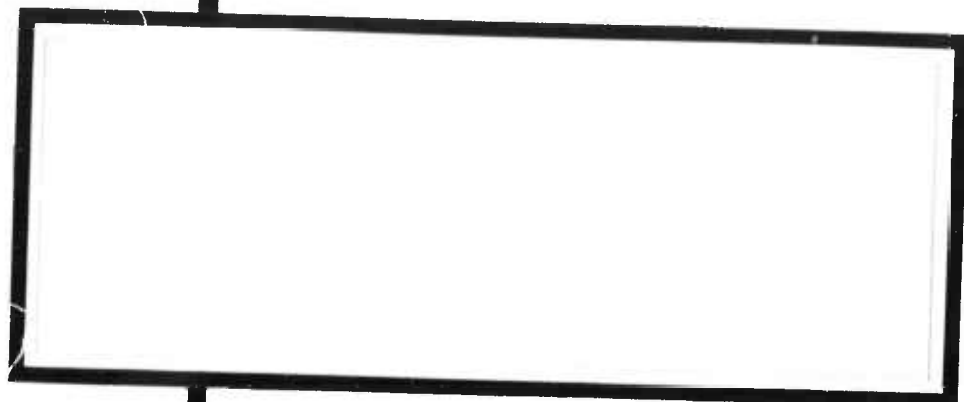Approved for public release; distribution is unlimited.

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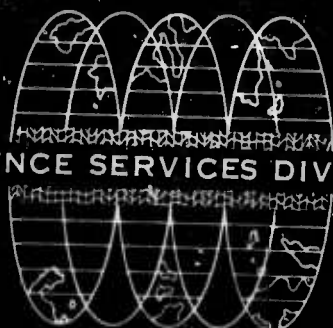
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AN EXPERIMENT IN
EVENT DETECTION AND LOCATION WITH
LASA WAVENUMBER SPECTRA

ADVANCED ARRAY RESEARCH
Special Report No. 14

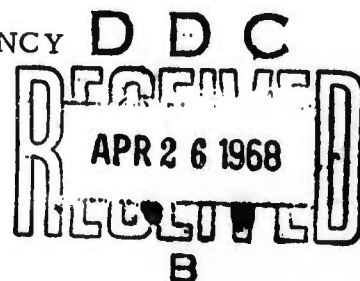Prepared by

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ABSTRACT

This report describes an experiment testing a technique for the simultaneous detection and epicenter location of seismic events. The technique, which consists of computing high-resolution frequency-wavenumber spectra for each of a series of adjacent or overlapping time gates, is applicable to any array station.

A LASA recording of a very weak teleseismic event was selected for the experiment. After examining the subarray straight-sum traces, a high-resolution wavenumber spectrum was computed at the frequency of peak signal energy for a single subarray. Epicenter location is more precise from the large-array wavenumber spectrum than from that obtained with a single subarray. However, the subarray spectrum yields a location sufficiently accurate for efficient postdetection processing at the network level and requires no preprocessing. The highly arbitrary preprocessing required for the detection and location of the event at the large-array level indicates the impracticality of using such a large array for this type of continuous worldwide surveillance.

It is concluded that continuous real-time computation of frequency-wavenumber spectra at each of a network of small-array stations would provide a most effective means of detecting and initially locating weak seismic events. More sophisticated postdetection network processing can then refine the estimate of epicenter and focal depth and can provide greatly improved event classification.

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TABLE

LIST OF ILLUSTRATIONS

LIST OF ACRONYMS

LASA   Large-Aperture Seismic Array

MCF   Multichannel Filter

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SECTION I
INTRODUCTION AND SUMMARY

Hypocenter location is usually accomplished by an iterative procedure which uses P-wave arrival times across a network of seismic stations. Event detection, while feasible at the network level, is usually accomplished at individual stations. Array stations have the capability to provide both improved event detection and some degree of epicenter location — a capability which is of great importance in the case of weak events initially detected at only one or two network stations.

The experiment described in this report tested a technique for the simultaneous detection and epicenter location of seismic events. The technique, which consists of computing high-resolution frequency-wavenumber spectra for each of a series of adjacent or overlapping time gates, is applicable to any array station. The technical monitor for the experiment selected a LASA recording of a very weak teleseismic event. Figure 1 presents straight-sum traces for 20 of the 21 subarrays.

A comparison of spectra obtainable from large and small arrays was also sought. Prior experience with LASA data had indicated that time anomalies across the large array were so large and so variable with source region that time-anomaly compensation would have to precede any coherent large-array processing. Therefore, after examining the subarray straight-sum traces, a single subarray was selected and, from its outputs, a high-resolution wavenumber spectrum was computed at the frequency of peak signal energy. A well-defined peak was obtained in the spectrum, and the epicenter corresponding to that wavenumber was noted. Wavenumber spectra computed over time gates of the same length both before and following the P wave confirmed that this spectral peak was due to the observed P wave.

Figure 1. Subarray Straight-Sum Traces with Marked
Large-Array Wavenumber Spectra Data Gates

A series of wavenumber spectra for adjacent time gates were then computed at the same frequency, using 19 subarray straight-sum outputs. Spectra were computed both with and without compensation for time anomalies. Compensation for average time anomalies was made for each subarray output, as determined by Chiburis.[*] Valid large-array spectra were not obtained until seven subarray outputs had been discarded as unusable because of either confirmed or suspected abnormal time anomalies.

Epicenter location was more precise from the large-array wavenumber spectrum than from that obtained with a single subarray; however, the subarray spectrum yielded a location sufficiently accurate for efficient postdetection processing at the network level and required no preprocessing (e.g., time-anomaly compensation). The highly arbitrary and personalized preprocessing required for detecting and locating this event at the large-array level indicated the impracticality of using such a large array for this type of continuous worldwide surveillance.

The conclusion is that continuous real-time computation of frequency-wavenumber spectra at each in a network of small-array stations provides a most effective means of detecting and initially locating weak seismic events. Then, more sophisticated postdetection network processing can refine the estimates of epicenter and focal depth and can provide greatly improved event classification.

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[*]Teledyne Industries, Inc., 1966: LASA Travel Time Anomalies for Various Epicentral Regions, Seismic Data Laboratory, Rpt. No. 159, Contract AF 33(657)-15919, 13 Sep.

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SECTION II
SMALL-ARRAY WAVENUMBER SPECTRA

Subarray C3 was selected for computing small-array wavenumber spectra to establish the approximate epicenter of the event. Selection was on the basis of best signal amplitude on the straight sums. Outputs of all elements of subarray C3 were demultiplexed and plotted as shown in Figure 2.

Some variation in signal amplitude and waveform is observed; this is characteristic of the LASA. While time anomalies at the LASA site can be significant across the dimensions of a subarray, there is usually only a small signal loss when applying subarray processing techniques based on the plane-wave assumption.

Since the object of the experiment was to test the feasibility of using wavenumber spectra for detection and initial location of weak events by a single network station, no preprocessing of the C3 outputs was performed. Ordinarily, the high-resolution technique for computing wavenumber spectra is sensitive to departures from the plane-wave assumption; however, an averaging procedure recently shown to provide a much more robust spectral estimate was planned for the initial wavenumber estimate.

Use of frequency-wavenumber spectra for event detection requires computation at several frequencies over the P-wave signal band. These frequencies should differ by less than the half-power width of even the most narrowband P waves. The frequency range of interest will be station-dependent to some extent.
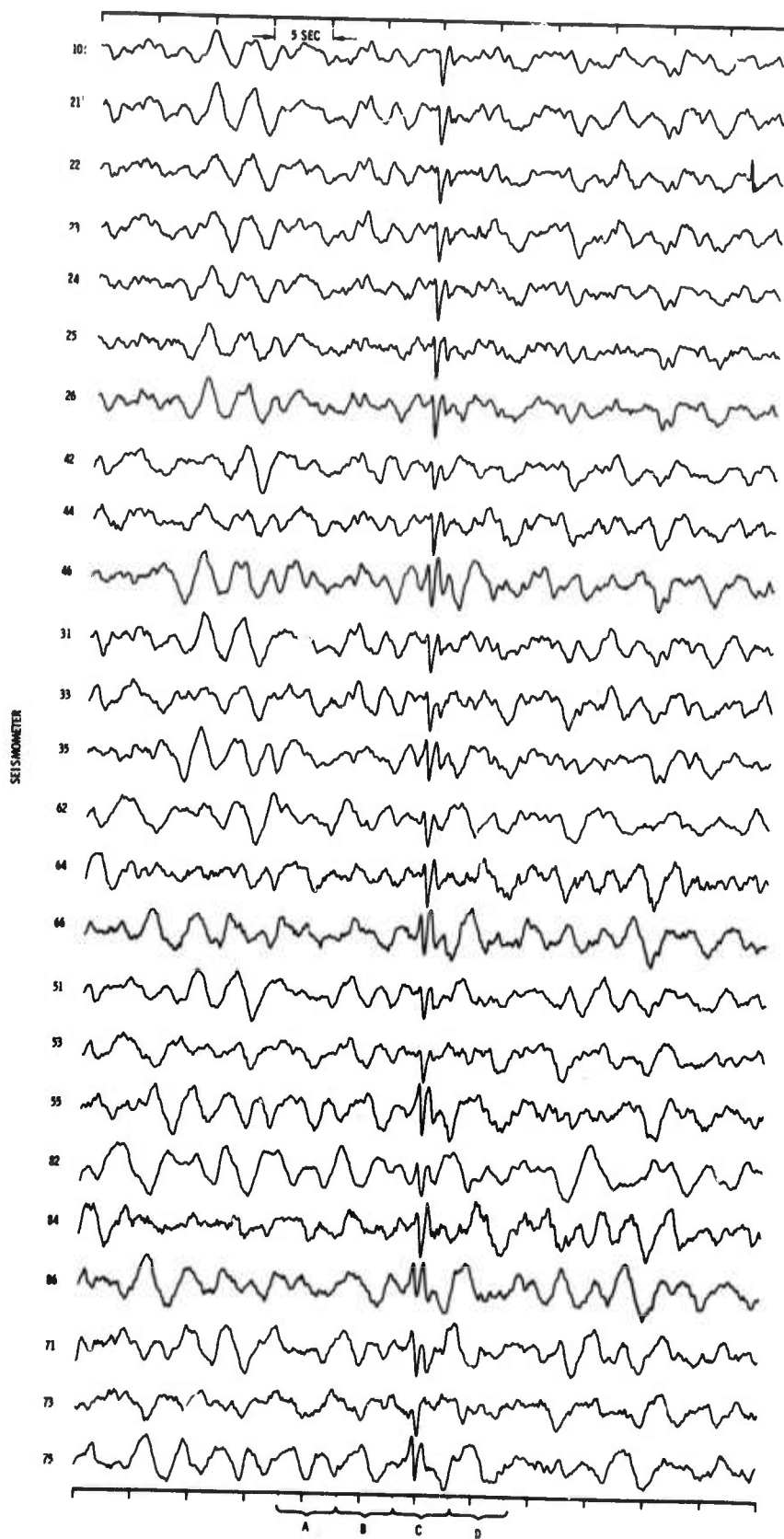
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Figure 2.   Subarray C3 Traces with Marked
Wavenumber Spectra Data Gates

The energy-density spectrum of the P wave is estimated by computing and comparing spectra of noise and signal plus noise (Figure 3). The ambient noise power-density spectrum is estimated from 50 sec of noise preceding the signal; the signal-plus-noise spectrum is estimated from 5 sec of data commencing just ahead of the P wave. The output of a single seismometer (62) is used to avoid the spectral distortion produced by the out-of-phase addition of signals and noise components when the straight sum is formed. Signal energy is observed from 0.5 to 5.0 Hz and reaches a maximum at 0.85 Hz. The half-power width of the dominant peak in the signal energy-density spectrum is approximately 0.5 Hz. To conserve computer time, wavenumber spectra in this experiment are computed only at 0.85 Hz.

The first set of wavenumber spectra of this event are computed from the 5 sec of subarray C3 data containing the P wave and marked interval C in Figure 2. Since the high-resolution technique requires selection of one array element as reference and since this selection affects the wavenumber spectrum obtained, six spectra are computed using different seismometers as reference. The variation with choice of reference sensor is due to departures from space stationarity and to an effect determined by the relationship between source azimuth and seismometer location. Departures from space stationarity are caused primarily by seismometer inequalization and geologically induced time and amplitude anomalies. The second effect arises because of a loss of degrees of freedom in MCF design when the reference sensor is not on the same or opposite side of the array as the source.
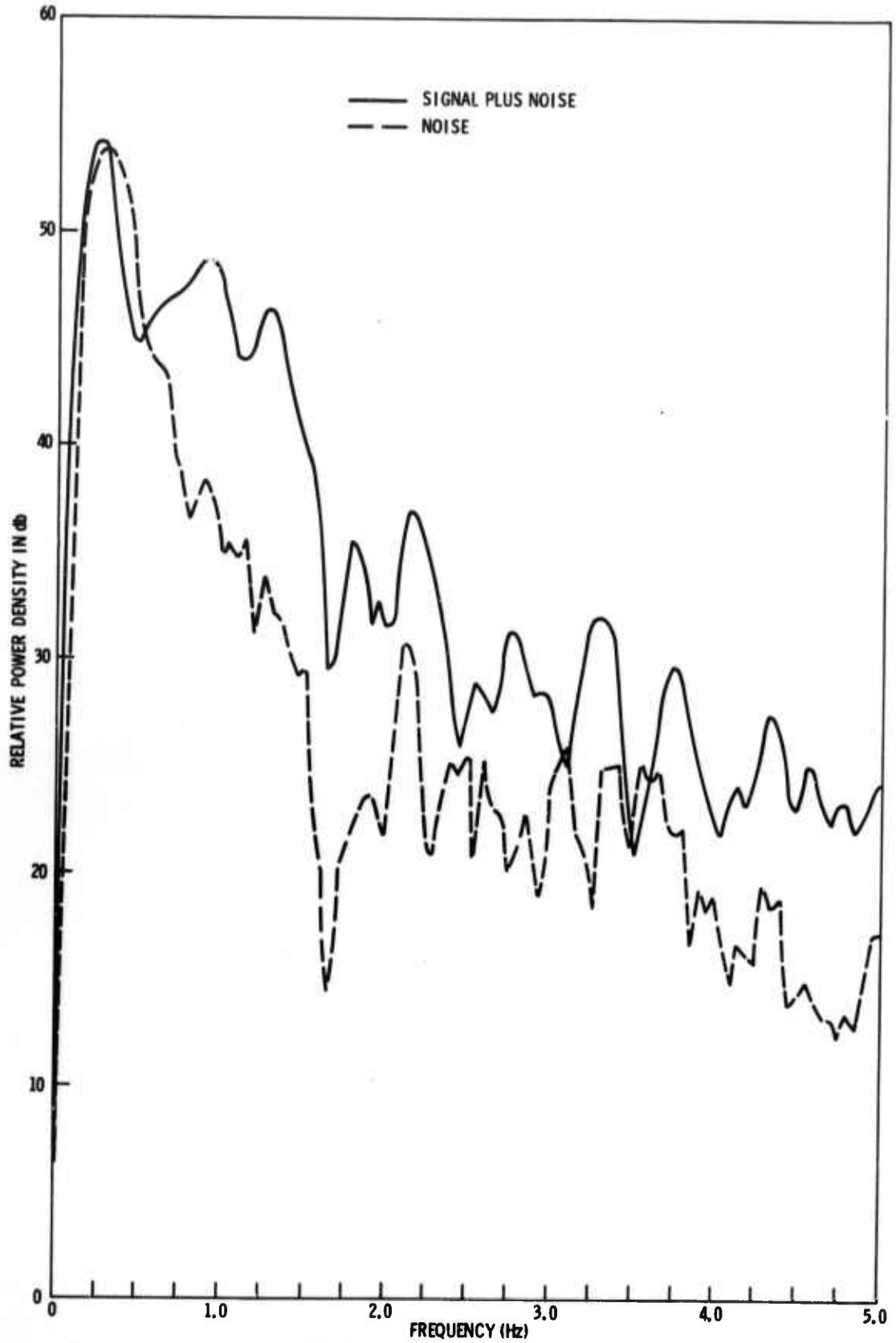
Figure 3.   Single-Seismometer Power-Density
Spectra of Noise and Signal Plus Noise

The six C3 P-wave spectra are shown in Figure 4. Four of the spectra are seen to peak at approximately the same wavenumber. The two which are expected to suffer from a loss in degrees of freedom show the most variation. All spectra exhibit the characteristic elliptical peak for which the major axis is perpendicular to the line from reference sensor to array center. In view of the elongated peaks, none of these spectra give an unequivocal wavenumber estimate; the variability between spectra suggests low reliability of any such estimate.

The variation with choice of reference sensor has been observed to be greatly minimized when compensation for seismometer inequalization and signal anomalies is provided; in the absence of such information, the spectral estimate may be stabilized also by averaging the spectra obtained using several different reference sensors. Wavenumber resolution is not lost through averaging since, if the selected reference sensors are distributed fairly uniformly around the perimeter of the array, a circular peak (thus, a more unequivocal wavenumber estimate) is obtained.

Figure 5 presents the wavenumber spectrum obtained from the average of the six MCF wavenumber responses used to obtain the six spectra of Figure 4. Also shown for comparison is a spectrum computed by the conventional technique.* The wavenumber estimate provided by the conventional spectrum is appreciably less than the wavenumber corresponding to the known epicenter of this event if the point of peak power-density is used.

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*As the term is used in this report, the conventional technique for estimating wavenumber spectra requires premultiplying and postmultiplying the measured crosspower matrix by the row and column vectors, respectively, having i^{th} elements of $\exp(j \vec{k} \cdot \vec{x})$ where $\vec{k}$ is the wavenumber vector and $\vec{x}_i$ is the location vector for the ith sensor.
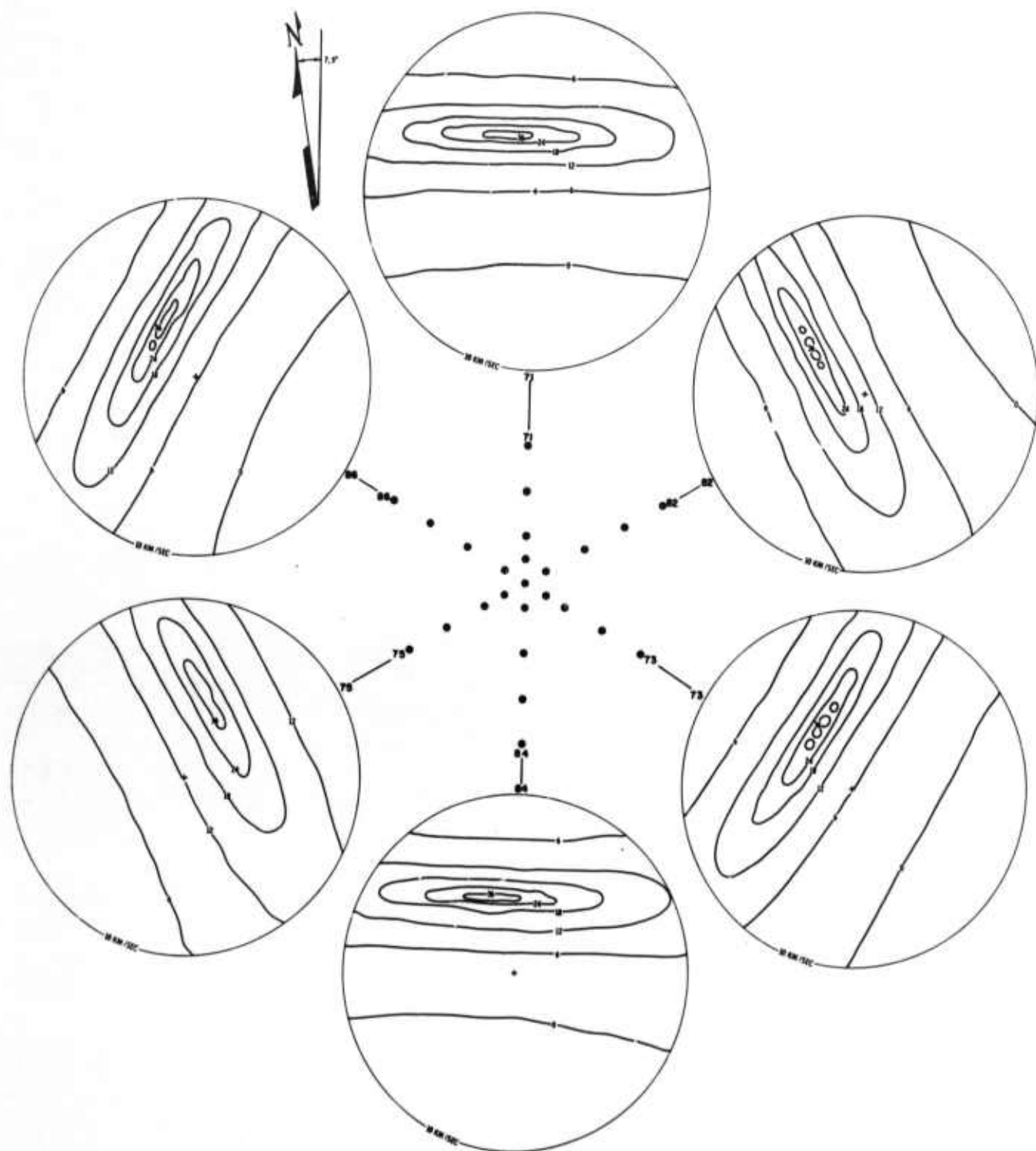
Figure 4. High-Resolution Subarray C3 Wavenumber Spectra
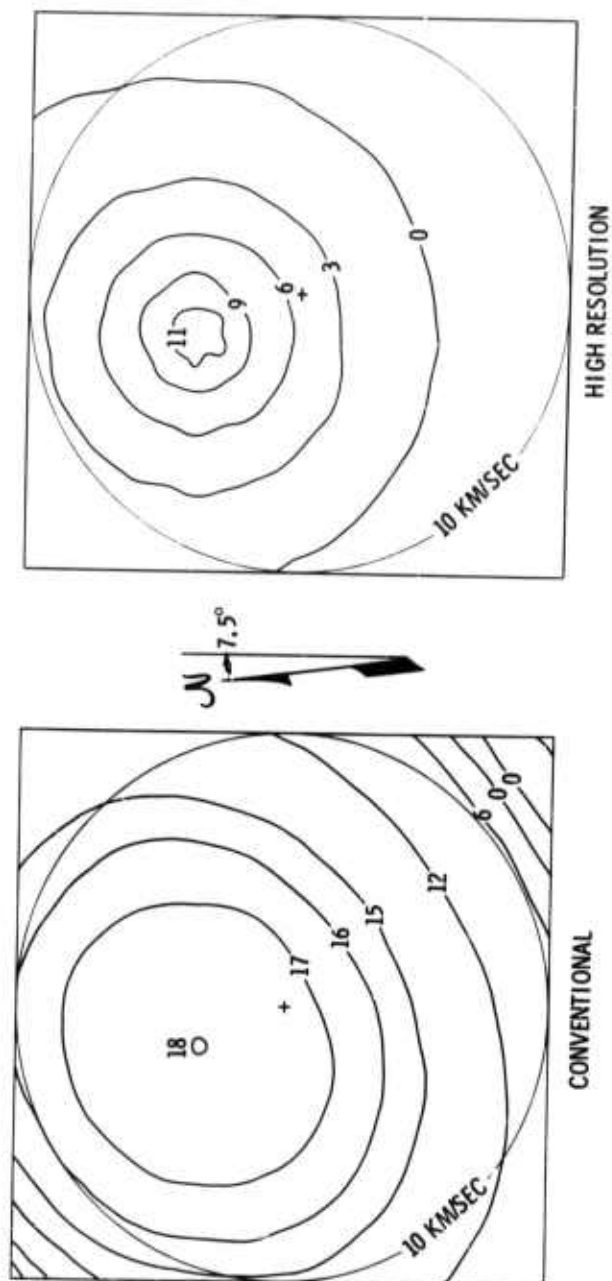at 0.85 Hz, Using Six Different Reference Sensors

Figure 5. Conventional and High-Resolution Subarray C3 Wavenumber Spectra at 0.85 Hz

Although not visible in Figure 5, the high-resolution spectrum lacks the highly undesirable sidelobes prominent in conventional spectra.[*] These sidelobes can easily prevent detection of a weak event in a coherent noise field. The narrower half-power width of the high-resolution spectral peak is obviously preferable for event location. The high-resolution-spectrum maximum occurs at a wavenumber corresponding to a P wave from an event at azimuth of 344° and at a distance of 93°. The reported epicenter is at an azimuth of 348° and at a distance of 91.8°. This location accuracy is very good, since there has been no compensation for time or amplitude anomalies.

To determine the detectability of the event using wavenumber spectra, additional spectra before and after the P wave are also computed. Data for these spectra consist of intervals A, B, and D of Figure 2. The spectra are not averages but are individual spectra derived with respect to a single reference, i.e., seismometer 84. These three spectra, as well as the signal spectrum derived from interval C with seismometer 84 as reference, are presented as Figure 6. The reference power, though arbitrary, is the same for all four spectra. The peak corresponding to the P wave is seen to be 19 and 22 db, respectively, higher than the high-velocity maxima obtained for ambient noise intervals A and B.

The event clearly would have been detected by any sort of thresholding of the wavenumber spectrum. The lack of similarity between the two noise spectra is probably due primarily to the noise field being non-time-stationary over such short time intervals.

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[*] Texas Instruments Incorporated, 1966: High-Resolution Wavenumber Spectra with Applications for Detection and Location of Weak Signals, Study of Statistical Discrimination between Earthquakes and Explosions, Scientific Rpt. No. 1, Contract AF 19(628)-4173, 30 Jun.
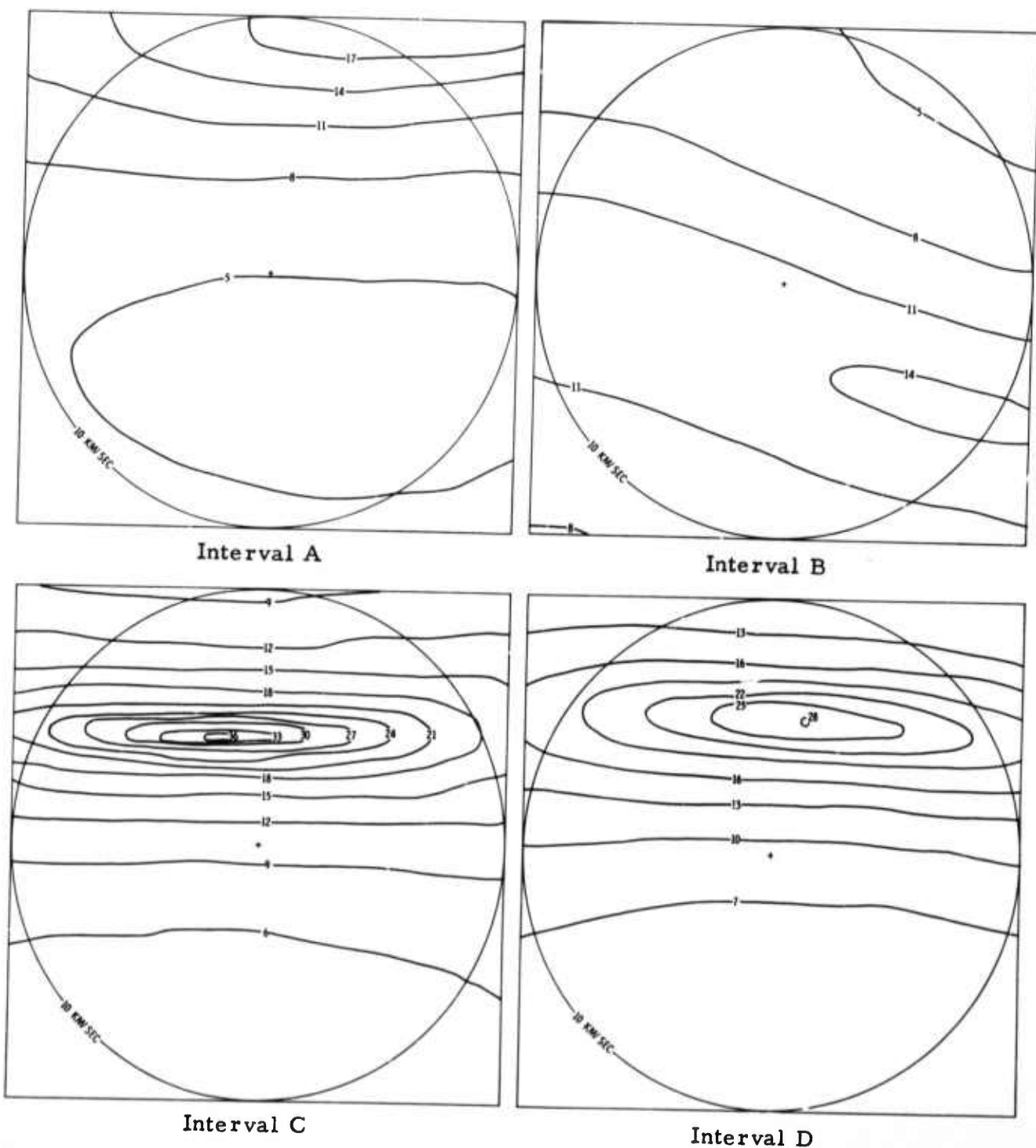
Figure 6. High-Resolution Subarray C3 Wavenumber Spectra Computed at 0.85 Hz for Four Consecutive Data Gates

The wavenumber spectrum corresponding to interval D exhibits a relatively strong peak to the northeast. This peak may be due to another teleseismic event arriving from that direction but is more likely due to scattered signal energy or multipath. The fact that this peak does not appear on the large-array spectra (shown later) supports the scattered-signal theory. Lack of evidence of further coherent energy from the event epicenter indicates a relatively simple event.

SECTION III

LARGE-ARRAY WAVENUMBER SPECTRA

Several approaches to computing wavenumber spectra at the large-array level have been made. All approaches use the 60 sec of sub-array straight-sum data indicated as interval C in Figure 1.

In the first attempt, straight sums from 19 subarrays (D3 is spiky; E4 is suspect) are used, with no compensation for time anomalies. No peaks are observed in the spectrum at apparent horizontal velocities greater than 10 km/sec. The failure to detect a peak corresponding to the P wave is not unexpected. Previous work with LASA data indicates that most events exhibit rather large time and amplitude anomalies which are approximately the same for events from the same general region. Large time anomalies degrade or completely destroy a high-resolution wavenumber spectrum which is based on the plane-wave assumption.

The next approach, therefore, uses the same data; however, compensation for expected time anomalies is provided. Expected time anomalies are the average time anomalies compiled by Chiburis for the region nearest that indicated by the subarray C3 spectrum for which time anomalies are available.[*] The large-array spectrum so obtained still fails to provide any indication of a teleseismic source.

An investigation of observed time anomalies for this event has uncovered the reason for the poor large-array performance. Observed travel-time anomalies are determined from crosscorrelations of narrow bandlimited subarray straight sums. All subarray outputs are crosscorrelated with the subarray A0 output and relative signal arrival times determined from the correlation lag at which the maximum occurs. Table 1 shows both theoretical and observed relative arrival times. These relative arrival times,

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[*] Op cit, Teledyne Rpt. No. 159.

when compared to those expected for a P wave from the epicenter estimated from the C3 spectrum, yield the observed time anomalies. The expected anomalies for subarrays B1, B4, C1, and F1 are -0.06, 0.05, -0.04, and -0.11 sec, respectively.

The observed anomalies for these four subarrays are in such poor agreement, given the time-anomaly variances for this source region, that it must be concluded that either the observed anomalies were invalid or that time shifts were inadvertently introduced when the data were multiplexed and recorded. Without further attempts to explain these unexpectedly large anomalies, the four subarrays were eliminated from further large-array processing. Since subarrays C4, E2, and F2 showed no evidence of the P-wave signal, these subarrays also were discarded.

Another attempt to compute a valid large-array spectrum uses the remaining 12 subarray straight sums (indicated by asterisks in Figure 1). Time anomaly compensation using Chiburis average time anomalies is provided.

Spectra computed for three consecutive 60-sec time gates are presented in Figure 7. Each spectrum is the average of 12 individual spectra, each using a different subarray as reference. The average is obtained directly by a computational shortcut.* All three spectra show peaks approximately 3 or 4 db above the background, which correspond to other events or to coherent noise sources. A peak is observed at the expected wavenumber in the spectrum for interval C. The maximum peak corresponds to an epicenter at an azimuth of 349° and at a distance of 91°. It is doubtful that this peak would have been detected by any type of detection procedure. Note, however, that a 60-sec data gate has been used; a data gate of about 15 sec would probably produce higher signal peaks.

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*Texas Instruments Incorporated, 1968: An Evaluation of the Use of High-Resolution Frequency-Wavenumber Spectra for Ambient Noise Analysis, Advanced Array Research, Spec. Rpt. 8, Contract F33657-67-C-0708-P001, 15 Feb.

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Table 1

P-WAVE TRAVEL-TIME ANOMALIES (IN SEC) FOR EACH SUBARRAY RELATIVE TO SUBARRAY A0

Sub-Array	Expected Time for Plane-Wave	Observed Time	Observed Anomalies	Expected Anomalies	Difference
B1	+0.2	±1.6	+1.4	-0.06	+1.5
B2	-0.3	-0.2	+0.1	-0.04	+0.1
B3	-0.1	+0.1	+0.2	+0.04	+0.2
B4	+0.4	+1.9	+1.5	+0.05	+1.4
C1	+0.6	+2.0	+1.4	-0.04	+1.4
C2	-0.2	-0.1	+0.1	-0.10	+0.2
C3	-0.5	-0.3	+0.2	+0.02	+0.2
C4	+0.3			+0.13	
D1	+0.5	+0.4	-0.1	-0.07	0.0
D2	-0.9	-0.6	+0.3	+0.17	+0.1
D3	-0.5			+0.30	
D4	+1.2	+1.6	+0.4	+0.03	+0.4
E1	+2.1	+2.1	0.0	-0.17	+0.2
E2	-1.2			+0.11	
E3	-2.4	-2.9	-0.5	+0.51	-1.0
E4	+0.7			+0.64	
F1	+3.0	+2.1	-0.9	-0.11	-0.8
F2	-3.5			+0.48	
F3	-2.4	-2.0	+0.4	+0.68	-0.3
F4	+4.0	+3.6	-0.4	+0.47	-0.9

(+) Implies energy arrived at indicated subarray before it arrived at subarray A0

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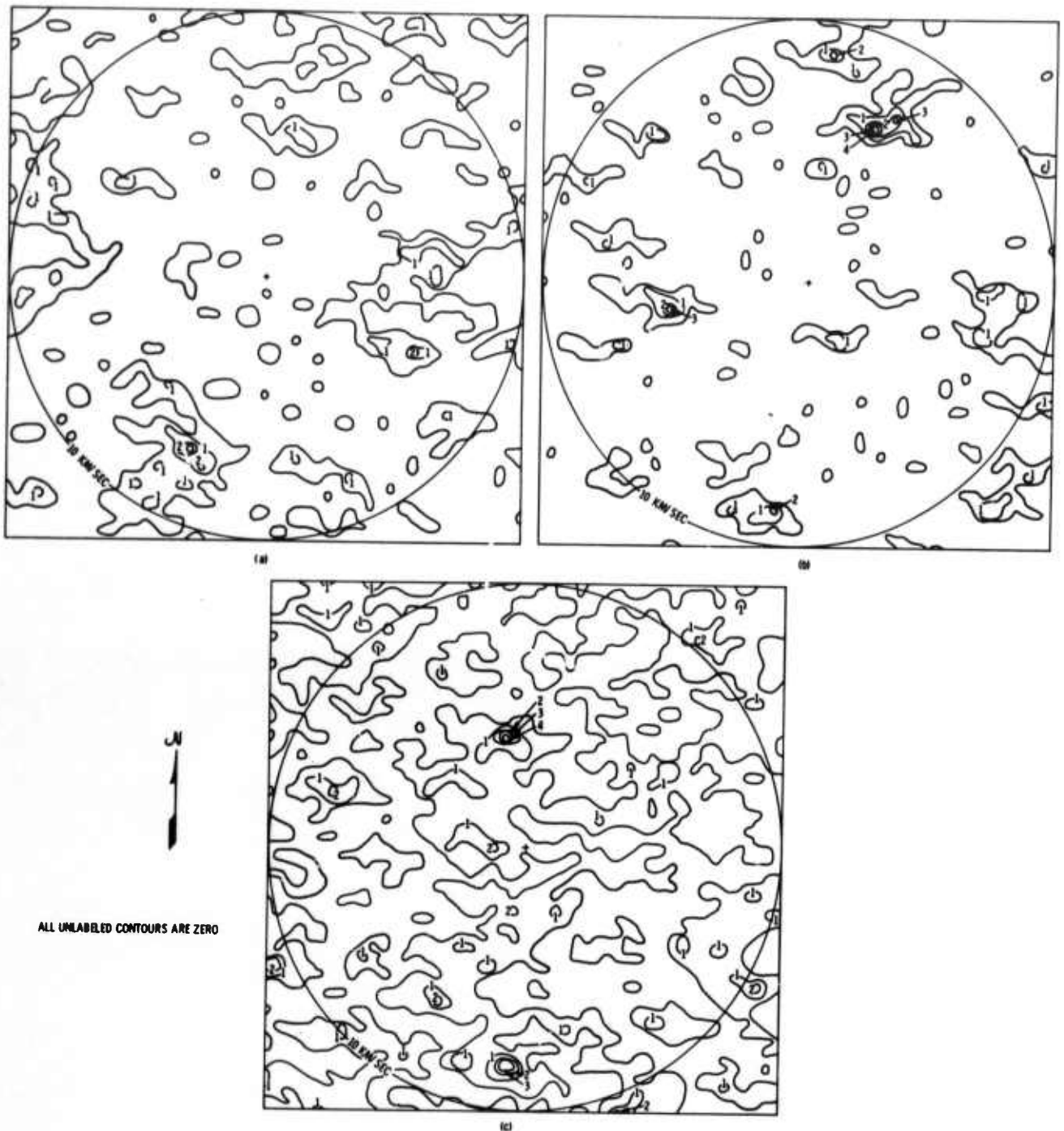
Figure 7. Large-Array High-Resolution Wavenumber Spectra
at 0.85 Hz for Three Consecutive Data Gates

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This estimate of event epicenter, achieved using average time anomalies, is within 1° in both azimuth and distance. Considering that the average time anomalies are based on eight events only (most of which are about 15° from the estimated epicenter), the precision in location is considered quite good. With time anomalies based on events from the same region, this location probably could be improved.

It can be concluded, therefore, that small arrays can give sufficiently good location, with no preprocessing, to establish source region and that larger arrays using average time anomalies can then locate epicenters well within 1°. Much less processing at the network level would be required to establish exact epicenter and to classify the event if a single high-quality array provided an epicenter estimate accurate to within 1°.

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SECTION IV
CONCLUSIONS

The results of this experiment cannot be generalized to make positive conclusions as to the feasibility of using wavenumber spectra for event detection and location at any array station. Some valid conclusions are possible, however, regarding the feasibility at LASA.

The subarray wavenumber spectrum, with no preprocessing, provides excellent detection and location of this weak event. The large-array wavenumber spectrum provides poor detection and good location — but only after elaborate and highly arbitrary preprocessing. Thus, the use of subarray data for continuous on-line computation of wavenumber spectra appears quite feasible, while use of large-array data does not.

The choice of subarray C3 was an arbitrary choice, and another subarray probably would not have yielded such a good spectrum. It is well-known that the various LASA subarrays vary greatly in their sensitivity to events from particular regions and that this pattern is very dependent on source region. A subarray which is particularly sensitive to events from one region may be very insensitive to events from another region, while some other subarray may be the opposite. Optimum use of this technique at LASA, then, might require computation of wavenumber spectra for several subarrays. Naturally, the best subarray for each region to be monitored would be selected. An alternate approach would be the computation of wavenumber spectra from large-array data for which signal equalization preprocessing had been performed.

The use of wavenumber spectra at stations consisting of a single, relatively small array would undoubtedly result in detection thresholds varying with event source region. However, any other detection and location procedure based solely on data from that same array would show the same dependence on source region. Properly computed wavenumber spectra can detect events at or below the detection threshold of other techniques[*] and can provide accurate epicenter location.

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[*]Texas Instruments Incorporated, 1967: Research on High-Resolution Frequency-Wavenumber Spectra, Large-Array Signal and Noise Analysis, Spec. Scientific Rpt. No. 2, Contract AF 33(657)-16678, 20 Apr.

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13. ABSTRACT

This report describes an experiment testing a technique for the simultaneous detection and epicenter location of seismic events. The technique, which consists of computing high-resolution frequency-wavenumber spectra for each of a series of adjacent or overlapping time gates, is applicable to any array station.

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It is concluded that continuous real-time computation of frequency-wavenumber spectra at each of a network of small-array stations would provide a most effective means of detecting and initially locating weak seismic events. More sophisticated postdetection network processing can then refine the estimate of epicenter and focal depth and can provide greatly improved event classification.

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